12. Colour-production in relation to the Coloured Feathers of Birds. By A. Mallock, F.R.S., F.Z.S.

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(Text-figures 1–4.)

The brilliant colouring of many birds and the forms of the feathers on which this colouring appears, present many points of interest both in regard to the means by which the colour-effect is produced, and to the processes of selection which have led to their development.

In the present note I touch only on the physical side of the problems, and hope to give some idea of the many ways in which colour may be produced by the action of white or composite light on matter, and of the effect of the forms of various feathers in modifying the appearances which the more intimate structure of the material produces on the incident light.

If any object appears coloured when viewed in white light, it shows that the matter of which it is composed exercises some selective action on the composite light falling on it, absorbing or transmitting certain colours and reflecting or scattering the remainder. This selection may be of two kinds: namely, a relation between the periods of light of various wave-lengths and the molecular periods of the matter on which it falls, or on a relation between some distance or spacing in the structure of the substance and the wave-lengths themselves.

The first of these relations includes all pigment colours, and the second those which are known as interference effects.

In the following table I have given a list of all the types of colour-production with which I am acquainted, and I believe that these will cover every known case, although the actual dynamics of a large proportion are very doubtful, involving as they do the dynamics and constitution of the molecule.

Colour may be produced by:—

I.

A relation between the periods of waves of light and the molecular periods of the colour-producing matter:

	Examples.
Dispersion, *i.e.* dependence of wave velocity on wave-length.	Prismatic Colours, Rainbows, etc. Powdered glass or other colourless transparent material immersed in a fluid of the same mean refraction index but different dispersive power.
All dyes and pigments, which may be transparent and scatter or transmit waves of certain periods and absorb the remainder.—— *Or*:—	The greater number of coloured solids and fluids.
Reflect certain periods and transmit the remainder.	Aniline colours in crystal or dry films, and many other crystals.

Are opaque and reflect certain periods and absorb the rest.	Opaque pigments such as lead chromate, etc.
Complete opacity may arise either from the absorption of all wave periods or by complete reflection.	Lamp-black. Silver and most white metals.
Fluorescence and Phosphorescence.	

II.

A relation between the wave-lengths of light and the structural dimensions of the matter which appears coloured :

	Examples.
Reflection or transmission from or through a striated or laminated structure.	Colours of thin plates. Mother-of-pearl. Lipmann films. Diffraction gratings. Pitted surfaces with pits of uniform depth.
Scattering or transmission of light by particles of sizes comparable with the wave-length, but irregularly distributed.	Red of sunset. Light, seen through vapours or emulsions. Blue sky and the colours of the sea and rivers. Glass coloured with gold. Supernumerary rainbows.

III.

The colours of polarization in most cases depend both on molecular structure and on the linear dimensions (measured along the paths of the rays) of the bodies which exhibit them.

With regard to the first class, little is known concerning the intimate structure of matter. It is a fact, however, that light-waves travel more slowly in solids and liquids than *in vacuo*, and that the velocity is in some unknown way dependent on the wave-length.

In most cases this is best represented by assuming that the ether is, as it were, loaded by matter, while in some others it would appear that the elasticity of the ether is affected. The difference may be exemplified by a stretched string which has a definite period settled by its length, tension, and mass. If the string is loaded, the period is increased by an amount depending on the added load, but an equal increase in period may be produced by relaxing the tension. If the shape of a transparent body is such that the direction of light after passing through it depends on the velocity of the waves in the interior, as for instance in a prism or sphere, the emergent light will appear differently coloured in different directions.

In the case of pigments, it is most probable that the individual molecules have a natural period identical with that of some of the periods of the incident light, and that the colours which they reflect or transmit are due to resonance.

The actual dimensions, forms, and rigidities of molecules are unknown, but their diameters are apparently of the order of a ten-millionth of a centimetre; and one may inquire what the longest natural period of a sphere 1/10,000,000 cm. diameter would be if it were as rigid as steel, or, which comes to the same thing, what is its least natural frequency. Without going into the details of the calculation, it may be stated that this least natural frequency is somewhere about 5×10^{12} vibrations per second. All the other natural modes of vibration would have higher frequencies, and there is good reason to suppose that the rigidity of molecules far exceeds the rigidity of the matter formed by their aggregation. The frequency of yellow light is 5×10^{14} vibrations per second. Thus it seems that the natural frequencies of molecules and of visible light-waves are at any rate of the same order.

All these pigmentary and dispersion colours depend on the constitution of the molecule itself. In the second class it is the relation of the size of particles, or on their disposition in space as compared with the wave-length which determines the selective influence of the matter on white or composite light.

The origin of the colouring presented to view as the result of selective action of the structure on wave-length can be fairly well determined by the following tests:—

(*a*) Mechanical compression or extension.
(*b*) Immersion in various fluids.
(*c*) Change of colour with the angle of incidence of the light.

Of these, the compression test is the most decisive; for, if the mechanical distortion of the structure changes or obliterates the colour, it may be assumed that the colour itself depends on some special arrangement of the parts, and not on the molecular properties of the material of which it is built up.

There may be some apparent exceptions, as for instance when a material transmits one colour with less loss than another, so that the predominating colour is dependent on the thickness of the layer through which the light travels (*e. g.* manganese glass or a solution of chlorophyll).

In the circumstances, however, in which this test is applied to organic structures, such as feathers, these exceptions will hardly operate.

The greater part of the colours of feathers have their origin in pigments of the nature of which little is known. Except in one instance, no solvent has been found for them, and the pigments themselves vary much in physical properties. Some are nearly opaque, while others are transparent and transmit the complementary colour. Many, again, polarize the incident light, and this is especially noticeable with transparent yellows. These form rather brilliant objects when viewed between crossed nicols.

But by far the most brilliant colouring of birds has its origin in interference, that is to some periodic structure in the substance of the feather, where the spacing of the parts is a multiple of the half wave-lengths of the light they reflect. Such is the case among humming-birds, sun-birds, peacocks, birds of paradise, and ducks, to mention only a few instances of what are spoken of as "metallic" colouring.

All these colours disappear when subjected to pressure, and in all cases the colour-producing substance is confined to a very thin layer overlying an intensely opaque black or brown substratum.

The general effect when viewed from a distance depends to a great extent on the form of the surfaces on which the colouring layer is disposed. If these surfaces are planes, the relative positions of the eye and source of light with regard to the feather has to be rather carefully adjusted, in order that any colour may be visible.

When, however, the surfaces are rounded, the range of incidence is much extended, and from almost any point of view some colour appears, although the intensity is lessened, just as a tray of small glass beads will scatter sunlight in all directions although the intensity in any one direction is much less than what would be produced by a plane mirror adjusted to reflect lights in that direction only.

The examples chosen all show distinctive structure peculiar to the orders to which the examples belong.

A feather may be described as consisting of a stem, branches, and leaves (text-fig. 1) (named by zoologists respectively rachis, rami or barbs, and barbules, the latter sometimes as carrying barbicels). It is in the modifications of the leaves that the distinctive features are found.

I will notice these in order.

In all the ornamental feathers of Humming-Birds the branches, but especially those of the gorget, are so bent that their ends are parallel and the colour-bearing surface is on the leaves. A cross-section of the branches and leaves forms a succession of hollows in text-fig. 2 *e*.

The section of the leaves themselves is something like the numeral 7 (text-fig. 4 *c*), and the colour-producing material lies in a thin layer on the upper surface of the leaves, and is nearly a plane, so inclined that the normal makes an angle of about 60° with the branch, but lying in a plane parallel to the latter. (This angle varies in different species.)

To keep the leaves in this position, each barb terminates in a curved plate (text-fig. 4 *d*), which interlocks with the similar plates of the two or three leaves in advance.

Each branch ends in a long bristle (fig. 2 *b*), which, when the plumage is in good order, lies in the trough of the valley formed by the leaves and branches of the succeeding feather. This bristle is only found in the head- and gorget-feathers. The body-feathers, where coloured, end as shown in text-fig. 2 *c*.

From these arrangements it happens that the best display of colour occurs when the body of the bird is in the nearly vertical position it assumes when hovering.

In the Sun-Bird each leaf has a curious rasp-like shape, and the upper colour-producing surface is in the form of 3 or 4 convex plates, in each of which the virtual image of the sun or other source of light appears as a coloured spot.

The chief peculiarities of the metallic feathers of Birds of Paradise are that the leaves are only developed on one side of the branch, and are so disposed with reference to it as to be parallel to the stem (text-fig. 3 *b*). The upper surface consists of more or less rounded lobes, and the cross-section is shown in text-fig. 3 *c*. This, so far as I have observed, is the rule in all the metallic feathers, whether on the head, wings, or tail.

In the Rifle-Bird, which is a near connection of the Birds of Paradise, the leaves are only developed very slightly on that side of the branch on which, in the true Birds of Paradise, they are absent.

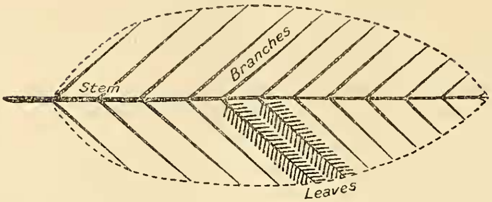
In the Peacock and all other pheasant-like birds, the leaves are of the form shown in text-fig. 4 *a*, *b*. The cross-section of the leaves is comma-shaped and the whole structure is transversely corrugated. The colour layer lies on the upper surface of the "dot" of the comma, which thus presents a series of rounded knobs to the light, each giving rise to a spot of colour.

In the head-feathers of Ducks the colour is developed on the leaves on both sides of the branch, but in the speculum, on one side only, the uncoloured leaves lying below the coloured part of the adjacent branch and serving to lock the two in position.

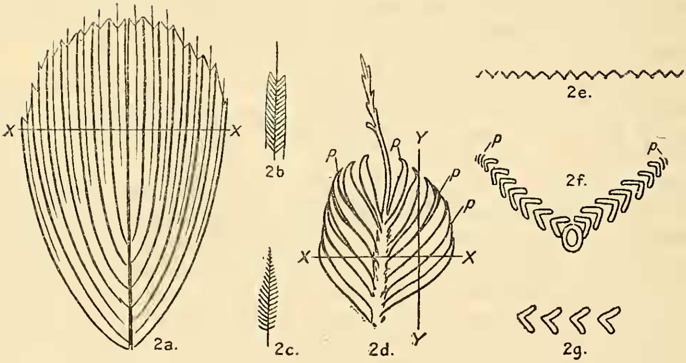
As before stated, all these feather colours disappear when the structure is compressed. For this test I place the feather between a quartz plate and a plano-convex lens of the same material, of a foot radius, these being mounted to fit on the stage of a microscope. The only difficulty in applying this test is to separate a suitable part of the coloured material on which to operate. The result is a conclusive proof that the colours are not due to any form of pigment, and strong evidence that they are due to interference. Most feathers are extremely impermeable to fluids, but in certain cases (the Peacock for instance), when immersion takes place, the colour changes at once to one of a longer wave-length: blue becomes green, green yellow, and so on. Where this happens it is evidence either that the feather is to a certain extent permeable by the fluid used, or, more probably, that the colour-production depends on some quality or grain of the outside surface.

The greater number of the metallic feathers which I have experimented with show no change on immersion in any ordinary

Text-figure 1.*



Text-figure 2.



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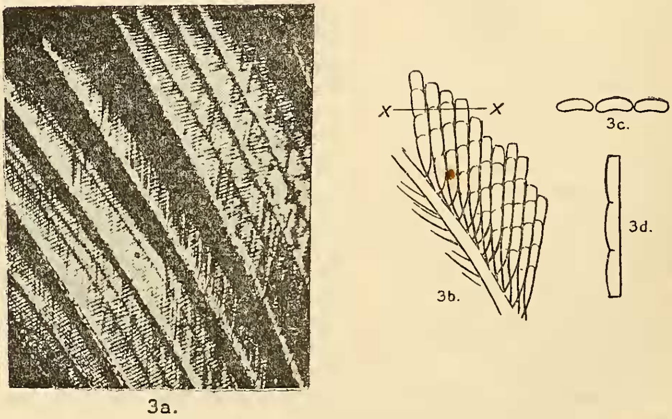

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* For description of the figures see next page.

Text-figure 4.

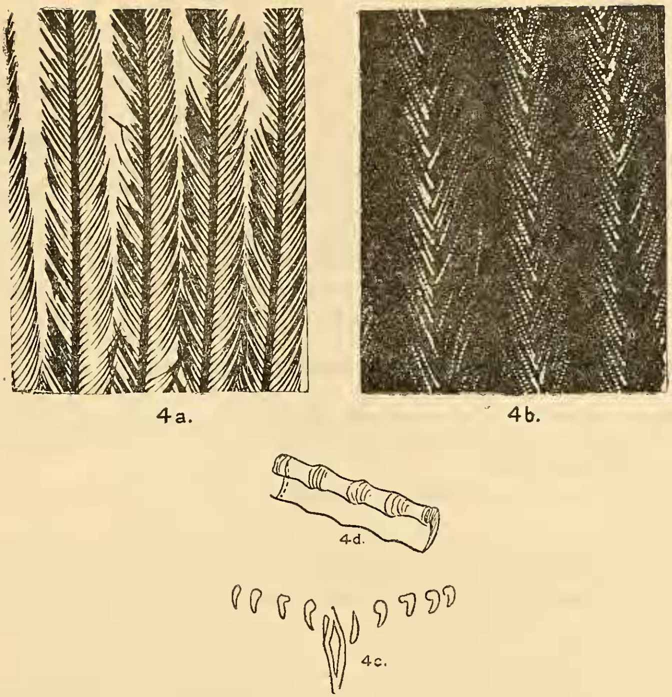

Fig. 1. Diagrammatic drawing of a Feather, showing Stem, Branches, and Leaves.

Fig. 2 *a*. Feather from the gorget of Humming-Bird (×20).

2 *b*. Termination of single branch of same feather (×30).

2 *c*. „ „ „ of coloured body-feathers from the same bird (×30).

2 *d*. Termination of gorget-feather (×130), showing the leaves and their prolongations (*p–p*), which serve to keep the former regularly spaced, and the planes of their upper surface inclined at a constant angle to the axis of the branch.

2 *e*. Cross-section of gorget-feather, parallel to the line X X of 2 *a* (×20).

2 *f*. Cross-section, parallel to X X of 2 *d*, of single branch of the same feather (×130). Note the sections of the prolongations of the leaves at *p p*.

2 *g*. Longitudinal section of the same, parallel to Y Y of 2 *d*.

Fig. 3 *a*. Feather from the wing of King Bird-of-Paradise by reflected light (×40).

3 *b*. Part of a single branch of same feather (×130), showing leaves developed on one side of the branch only.

3 *c*. Cross-section of leaves, parallel to X X in 3 *b* (×220).

3 *d*. Longitudinal section of one of the leaves of same feather.

Fig. 4 *a*. Branches of blue feather from Peacock's neck by transmitted light (×30).

4 *b*. The same by reflected light (×40).

4 *c*. Cross-section of single branch of same (×130).

4 *d*. Part of a single leaf of same, seen in perspective.

fluid (alcohol, xylol, chloroform, oil, etc.), but strong acids in time cause the colours to change towards the red end of the spectrum.

The most penetrative fluid which I have tried is the solution of iodide of mercury in iodide of potassium. This, when concentrated, rapidly destroys the feather substance, but in dilute solution merely penetrates into the interior. The gorget-feathers of the Humming-Bird (from Costa Rica) reflect a brilliant lilac, *i. e.* a mixture of red and blue, but after a few hours' immersion in the iodide solution, the red disappears and the blue changes to a very bright green.

All these metallic colours shift towards the blue as the angle of incidence of the light increases, as do the ordinary colours of thin plates; but this is not a proof that both have the same origin, for many of the aniline colours when in thin dry films show somewhat similar changes depending on the angle of incidence.

Michelson in America has compared the metallic colour of some beetles with those of the anilines, and has given reasons (connected with similarity of the polarization of light reflected by both) for believing that the origin of the colours in the two cases is of the same kind.

The pressure test, however, seems to make this conclusion invalid.

The colours seem to me to be more allied to those of Lipmann films, in which layers of reduced silver are spaced at half wave intervals, and in the case of metallic feathers I believe that one or two layers of optically dense material are the sources of interference.

Although half wave-lengths can be readily resolved by high-power microscopic objectives, it is almost impossible to cut sections thin enough (viz. less than ·00002 in.) to use with such powers. At least I have cut many hundred sections, but although in some cases a laminated structure seemed to be present, this was due to a diffraction effect. as was evident from the changes in the dimensions of position of the apparent lamina which occurred with the change of focal adjustment.

In the case of the Lipmann films, the layers of reduced silver are readily seen if the sections are expanded by wetting, though I have not been able to resolve them satisfactorily when dry.